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A Directed Energy System for Defeat of Improvised Explosive Devices and Landmines

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We describe a laser system, built in our laboratory at LLNL, that has near-term, effective applications in exposing and neutralizing improvised explosive devices and landmines. We discuss experiments with this laser, demonstrating excavation capabilities and relevant material interactions. Model results are also described.

Introduction

Landmines and improvised explosive devices (IEDs) pose severe challenges to successful military operations. A related capability is also needed for the disposal of unexploded ordnance. In general, the problem has three components: detection, exposure of the device (for example, by excavation), and neutralization of the device. Here we describe a laser system that specifically enables exposure and neutralization. It is compatible with state-of-the-art detection systems.

Our system utilizes a high-power Solid State Heat Capacity Laser (SSHCL), as built at LLNL [1] and shown in Figure 1. The impetus for this laser was to counter projectile threats on the tactical battlefield. Currently, our most advanced laser operates at a time-averaged power of about 34 kW. This can be extended to the 100-kW regime by straightforward additions to the hardware. The laser system is compact. We have designed a fully self-contained mobile concept, shown in Figure 2.

In our concept, destruction of a landmine or IED in a known approximate location is a two-step process [2,3]. First, the laser exposes the device. The beam can excavate soil by creating micro-explosions in the groundwater, as we have demonstrated in laboratory experiments. The beam can burn through other types of covering, such as canvas or vegetation.

Secondly, the beam is focused on the device. We have demonstrated that the beam can heat a metal container, or drill through a plastic container, leading to conditions for activation of a high explosive. For some IEDs, a simpler strategy might be merely to use the beam to cut electrical wires. Field operators would have detailed control over all such processes, by tuning the laser power and the spot size. In all cases, standoff would be limited only by the practical ability to sight the target.

Laser System

The laser contains of several (currently, 5) ceramic Nd:YAG slabs, pumped by High powered diodes, producing a current time-averaged optical power of about 34 kW. The wavelength is 1.064 μm. The laser operates at 200 Hz. The pulsed

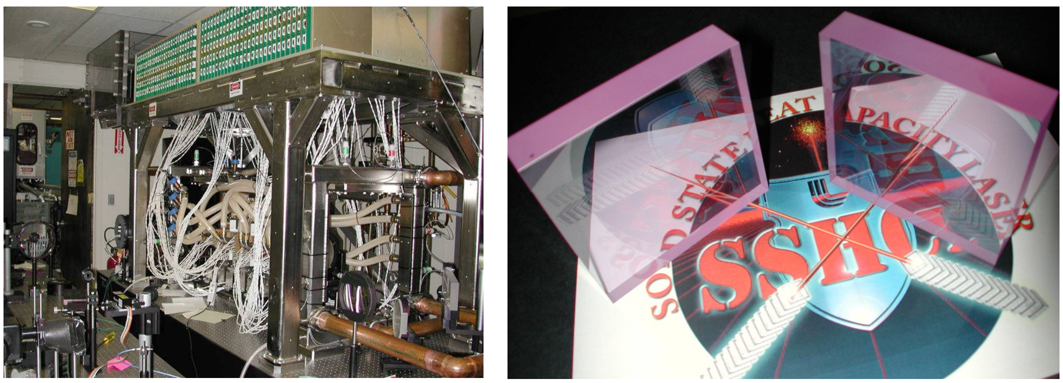


Figure 1. Left: The diode-pumped SSHCL, in the laboratory. Right: ceramic slabs (width 10 cm).

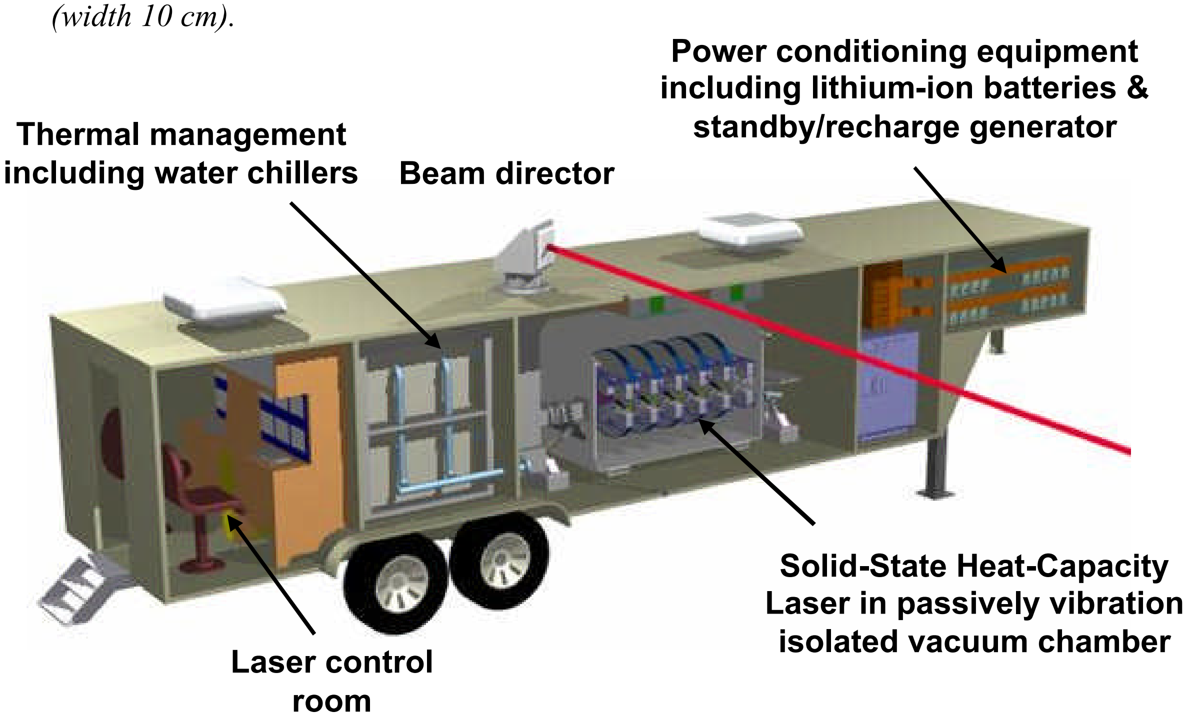


Figure 2. 100 kW mobile SSHCL concept: fully self-contained field operable concept.

format is crucial to the excavation capability. The pulse length is 0.5 ms, with pulse lengths of 1.0 ms being demonstrated.

This system is powered by lithium-ion battery modules, recharged in the field by the vehicle engine. No warm-up time is required for the laser. The logistical supply train is minimal. Speed of light engagement of targets coupled with silent and invisible operation are additional attributes of this directed energy technology.

The SSHCL has demonstrated significant power levels in the laboratory and holds the world record for average output power from a solid state, diode pumped laser (67 kW for short fire durations). This performance level, combined with its compact, scalable system architecture, allows for a variety of missions requiring mobile platform capability.

Shown in Figure 2 is our concept of a 100 kW SSHCL prototype, fully capable of performing live target kills in the field. This represents a field prototype device at a TRL 7 level of technical readiness (system prototype demonstration in an operational environment). Actual testing and usage in real application environments by those who would ultimately use the SSHCL on the battlefield is the next step in the evolution from the laboratory to such a device.

With IEDs and landmines constituting a significant threat in the Iraqi War, we believe that the SSHCL can provide the war fighter today with an important, new capability. We have developed a work scope, cost, and scheduling plan to produce a 1st field operational 100 kW prototype within a 12 month period. Additional mobile platforms such as a Future Combat System (FCS) vehicle, helicopter, fighter plane, and cruiser/destroyer are all viable candidates to house the SSHCL system.

Excavation Experiments

In excavation, the beam is absorbed by the soil, and heat is rapidly conducted to small quantities of groundwater. Vaporization of the water results in a micro-explosion which expels the surrounding soil. A single such micro-explosion is created by each laser pulse. The original size of the exploding volume is small compared to the beam size.

We have performed excavation experiments with a 1.5-kW SSHCL (3 Hz, 500 J/pulse). The pulses have a dramatic explosive effect. This is evident for 8 pulses into sand, as shown in Figure 3. The final hole is about 15 mm deep. The efficiency improved with spraying of additional moisture. The presence of organics, including roots, is expected to increase excavation efficiency. Soil compaction should also help, by gathering the moisture and organics into a

Figure 3. Interaction of 8 laser pulses with a sand target. The hole is about 30 mm in diameter and 15 mm deep.

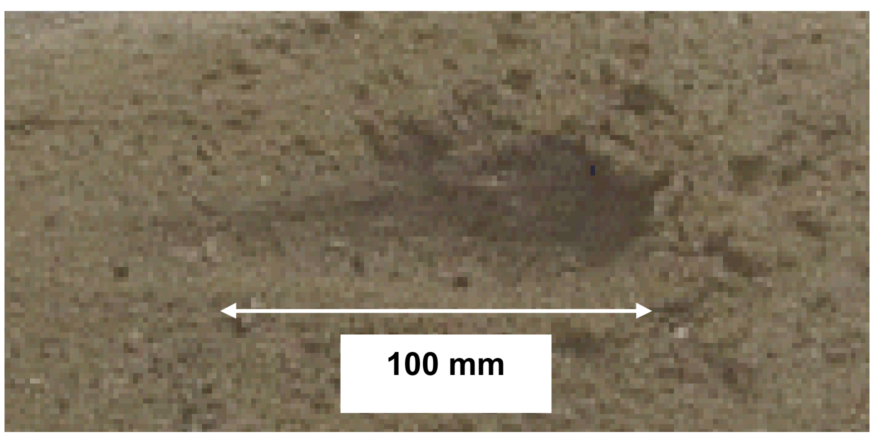


Figure 4. Channel dug in sand by 40 SSHCL pulses (each of energy 500 J), aimed from the left at 10^o to the horizontal. The channel has a length of about 100 mm, a maximum width of 36 mm, and a maximum depth of about 22 mm.

smaller volume. The removal efficiency is also expected to improve with pulse repetition rate, because of reduced heat leakage in the soil between pulses.

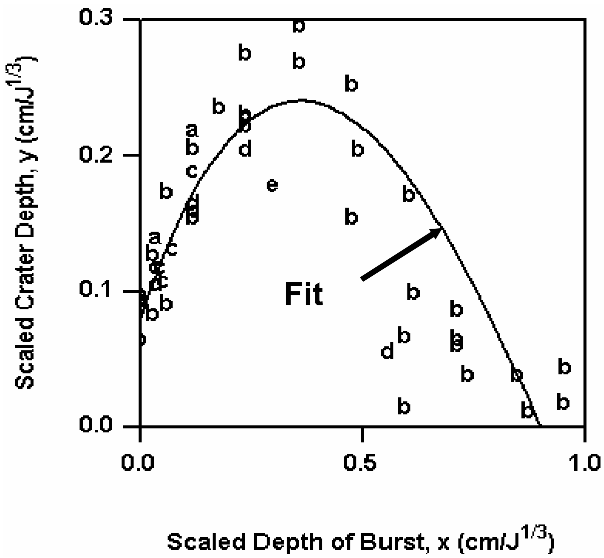
In field applications, the laser often will strike the ground at a shallow angle. We have performed experiments to test this situation, as shown in Figure 4. The first few pulses, which intercepted the soil at a glancing angle (initially 10^o), produced relatively little removal. Thereafter, however, a “backstop” of soil built up on the far side of the hole, nearly perpendicular to the beam. This increased the coupling of succeeding pulses, allowing for greater removal. On average, the volume removed per pulse (~ 1 cm^3) was about the same as for normal incidence.

Excavation Modeling

Excavation can be described in terms of scaling laws for explosions within a material [4]. One expects the size of the resulting crater to depend upon the blast energy E, the depth h of the blast, and the strength S of the material. The last three quantities determine a unique dimensionless combination $h(S/E)^{1/3}$. Since the material dependence is not varied here, we neglect S and work with the scaled depth $x = h/E^{1/3}$. Similarly, we expect that the depth d of the crater can be scaled in terms of the variable $y = d/E^{1/3}$. Thus we expect that the crater depth should be related to the burst energy and depth by a scaling law of the form $y = f(x)$.

This scaling dependence was indeed observed in a study of craters produced by bursts at the Nevada Test Site [4], as shown in Figure 5. The overall behavior has a simple explanation. A burst near the surface ($x = 0$) produces a crater of a particular depth. As the depth of the burst is increased, the crater at first increases. Beyond a certain depth, however, the burst tends to be contained. Eventually, containment is complete and no crater is produced. Note that the burst energies vary over three orders of magnitude.

Using this scaling, we can make predictions for the crater excavated by a single laser pulse. The burst depth is about the same as the absorption depth in soil, which is of order ~ 1 cm. The burst energy is a fraction of the pulse energy, determined by conduction in the soil and the distribution of groundwater. The details have been modeled [3] but are beyond the scope of this discussion. As shown in Figure 5, the crater depth is insensitive to the burst energy over the relevant range (a few hundred joules, depending on the laser power). It increases with burst depth but generally is of order 0.5 cm. Using a crater diameter about 4 times the depth [4], we obtain an excavated volume of about 1 cm^3. This agrees with the experimental estimate discussed in the previous section. Thus we have shown that laser excavation experiments can be quantitatively understood on the basis of explosive scaling laws.



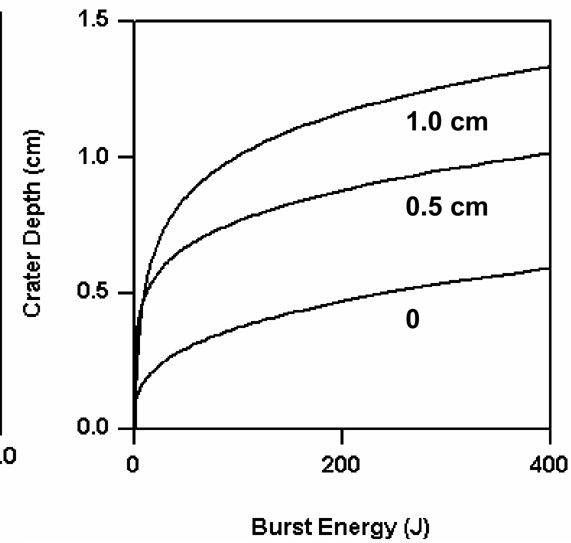


Figure 5. Left: Scaled crater depth versus scaled depth of burst, for 44 bursts at the Nevada Test Site [4]. Burst energies: **a**, *0.4 GJ (= 0.4 x 10^9 J);* **b**, *0.5 GJ;* **c**: *5 GJ;* **d**, *76 GJ;* **e**, *1900 GJ. (A ton of TNT is ~ 4.2 GJ.) The crater diameter is about 4 times the depth. Right: Calculated crater depth versus burst energy, for representative burst depths.*

Material Interaction Experiments

After exposing a mine, the SSHCL heats the casing. For a metal casing, the appropriate spot size is a few cm, giving a time-averaged intensity of a few kW/cm^2. Heat conducts across the metal on the time scale of a few seconds, followed by conduction (possibly across a tar or gap, depending on the design) to the HE itself. This method (rapid cookoff) is normally superior to drilling through the metal, in that less laser energy is invested in vaporization and the reaction gases are better contained, leading to a more thorough burnup of the HE.

We have performed a number of material interaction experiments, with realistic laser powers and spot sizes, to verify rapid cookoff. For safety reasons, explosives were not involved. (Experiments involving explosives, but with the laser source replaced with a thermite patch, have also been conducted at our laboratory.) In one laser experiment, a 21-kW beam irradiated a steel coupon, of thickness 1 cm, As shown in Figure 6, the rear temperature rose to about 750 C at 7 s (3 s after the beam has been turned off). If TNT were adjacent to the rear of the metal, then the explosive would have been initiated when a nearby volume reached about 600 C,

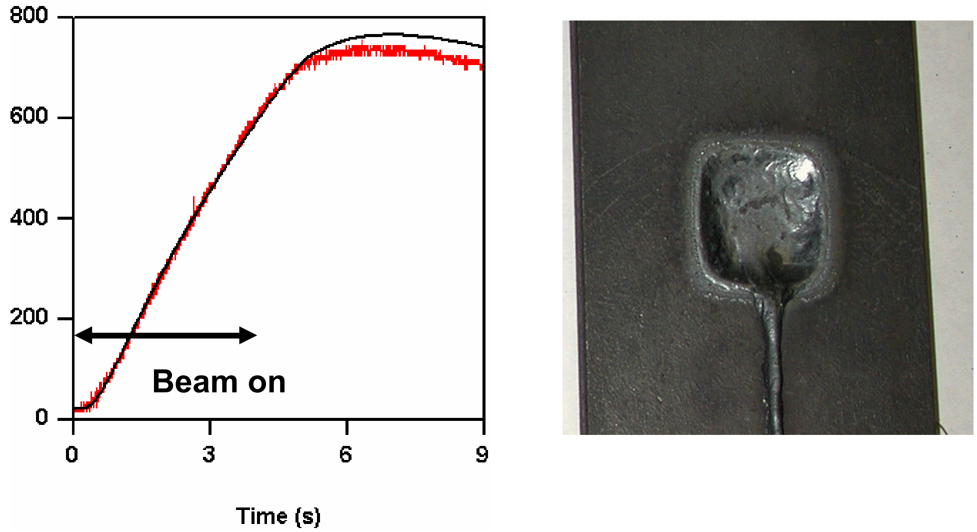


Figure 6. Left: Temperature of the back face a 1-cm steel coupon, heated by a 21-kW SSHCL beam, with a spot size of 2.9x2.9 cm^2. The red line indicates experiment, while the black line gives the model result. Right: coupon after experiment.

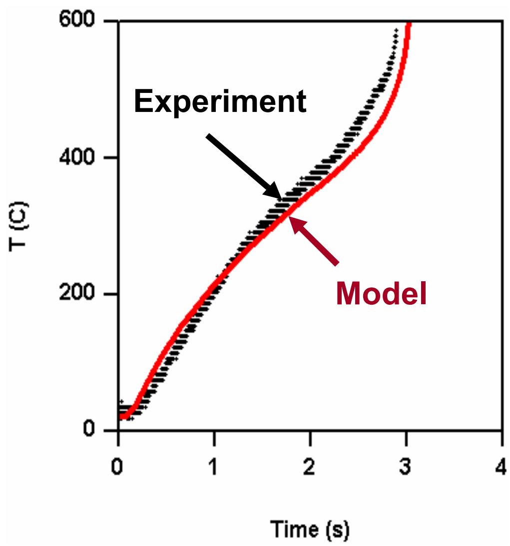
i.e. somewhat after 4 s. If the explosive were RDX, initiation would have occurred at about 400 C, or around 3 s.

Also shown in Figure 6 is the coupon after irradiation. The front face, unlike the back, has melted. Liquid has flowed from the spot under gravitational and viscous forces.

Figure 6 also gives the result of a simulation [5], based on optical absorption at the metal surface and thermal conduction, showing good agreement. The results are sensitive to the temperature-dependent absorptivity, which is poorly known. We have in fact used experiments like this to calibrate the absorptivity.

These predictions are conservative for an actual mine, since the casing is normally thinner than 1 cm. Under our conditions, the conduction time scales roughly with the thickness. On the other hand, mines inevitably have an insulating layer such as tar or air. Our modeling indicates that such a layer does not add appreciably to the initiation time, for reasonable choices of the parameter.

Another common metal in explosive devices is aluminum. Compared to steel, this has a lower absorptivity and a larger thermal conductivity, leading to weaker coupling and greater lateral heat losses. Nevertheless, the SSHCL can be very effective. Figure 7 shows the result of irradiating an aluminum coupon of thickness 1 cm with a 25-kW SSHCL beam, for 5 s. With a square spot size of



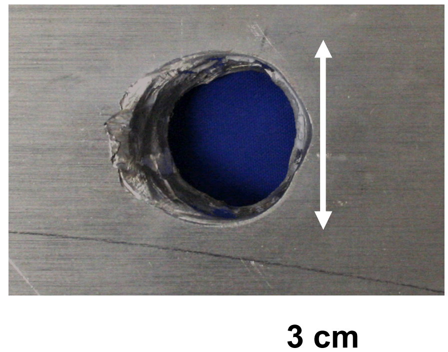


Figure 7. Left: Temperature on rear center of a 1-cm aluminum coupon, exposed to a 25-kW SSHCL beam (spot size of 2x2 cm^2). The coupon is penetrated shortly before 3 s. Right: resulting hole.

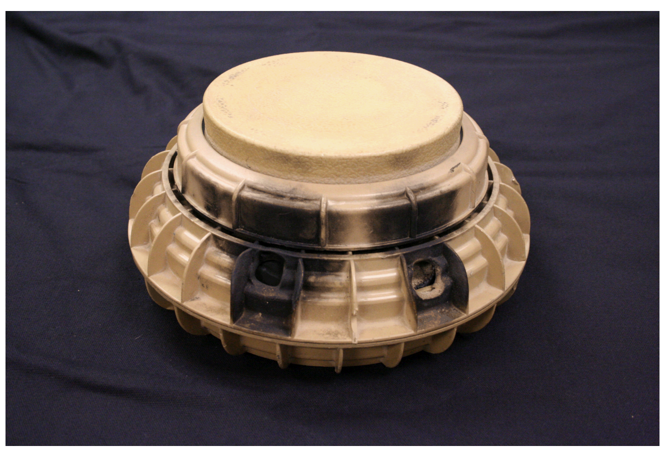


Figure 8. Holes resulting from irradiation of a plastic landmine casing at a laser power of 1.5 kW (two shots). The spot sizes are about 1 cm^2.

2x2 cm^2, the coupon is penetrated in less than 3 s, as dramatically shown both by the rear thermocouple trace and by the resulting hole. (This particular experiment involved air flow at Mach 0.3, but its effects were minor.) In comparison with the steel experiment, less violence would be expected from the HE reactions, since the hole would permit gases to escape. The modeling result is from the same code as used for steel, but with a different materials database.

We have also conducted laser irradiation of actual landmine casings, with the explosive removed. Figure 8 shows the result of illuminating a mine with a plastic casing for a few seconds, at a laser power of 1.5 kW. The casing was easily penetrated. Since flames were visible, we believe that the laser drilling was aided by combustion.

Comparison with Alternative Countermine Methods

Two other methods for the countermine application are high-caliber bullets and the ZEUS system.

With bullets, say of .50 cal, the necessity of repeatable, highly accurate aiming limits the standoff to distances of tens of meters. Our proposed system should extend this by at least an order of magnitude. Bullets are also less capable than the SSHCL system of rapid, precise excavation, and ricochets must be guarded against. The violence of the explosion is not controllable. A bullet is more likely to produce detonation than deflagration, along with a crater and collateral damage. An additional operational difficulty is that the ammunition, unlike photons, must be inventoried.

ZEUS is a 1-μm continuous wave laser system operating at a power of several kW. It has demonstrated the capability of neutralizing exposed ordnance, by heating metal containers or burning through plastics. However, this process may require several minutes for some targets. The SSHCL would be more rapid by roughly the ratio of the average beam powers. Finally, as a CW laser, ZEUS does not have the capability to excavate, unlike the SSHCL.

Discussion and Conclusions

We have proposed a directed energy system, based on a laser architecture now functioning in our laboratory, for defeat of landmines and IEDs. We have confidence in it by virtue of both experiments and modeling.

As our experiments indicate, a typical mine target could be neutralized within a matter of seconds. For IEDs, a covering material such as vegetation and/or canvas could be quickly burned away, followed by initiation of the explosive. These two steps might optimally be accomplished with different selections of beam power and spot size, which are easily controlled by the operator. In view of the great variety of targets, it would be useful to carry out a systematic experimental program leading to a practical handbook of strategies.

Because of the compactness and mobility of the laser system, it could readily be linked to various detection systems. These often produce large numbers of false positives. The laser operator could interrogate suspected targets quickly, by removing soil or by burning through objects such as roadside bags.

As we have noted, standoff from the target is limited only by the field of sight of the operator. Depending on the topography, the SSHCL vehicle might be situated on a hill, overlooking a wide area. In this case, it could coordinate with a number of detection operations.

Acknowledgments

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